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A VARIABLE TRANSFORMATION APPROACH TO IN-LINE pH CONTROL

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Abstract: Current practice and research into pH control principally entails the use of Continuous Stirred Tank Reactors (CSTRs). Whilst the over-design of this process does indeed damp out disturbances, it is expensive and leads to problems with control. Industry requires systems that are:

- economical, both in terms of capital and operating costs
- robust from a control point of view
- operable and flexible from a process point of view

pH control of neutralisation is a difficult non-linear control problem. This is largely due to the gross non-linear behaviour of pH measurement, but also due to the variable time delays inherent in the process. Non-linear processes have traditionally been controlled by a combination of linear control methods and gain scheduling. However in the last few years much progress has been made in the development of non-linear control systems. This paper outlines a variable transformation approach, that is an anti-logging technique which removes the non-linearity at source and yields an hydrogen ion concentration which is easier to handle.

Introduction

Many industrial processes entail the use of pH control. Applications are very diverse; Latrille et al¹ applied neural-networks to the production of lactic acid during the fermentation of milk and recently Deshpande et al² applied pH control to the wastewater from the sago industry. The most common process that calls for pH control is waste-water effluent treatment.

Historically the neutralisation process has largely been used as a test-bed for determining the effectiveness of innovative non-linear control methods. For example; Aoyama et al³ used the neutralisation process to examine a control affine model approach identified by fuzzy neural networks. Many advances have been made in non-linear control methods and can be considered suitable for pH control, as reviewed by Gokhale et al⁴. Another review by Bequette⁵ on the development of non-linear control systems utilised in the process industry also covered advanced methods applied to pH control.

Researchers in the pH control domain have mainly adhered to and concentrated on McMillian⁶ plant design advice. The processes are over designed and consist of

CSTRs. Research in this area is considered complete, as briefly demonstrated in a review by Nortcliffe et al⁷, although studies on existing plant continue. For example; Palancar et al⁸ recently reported on applying model reference adaptive control to neutralising a variety of streams of weak and strong acids with buffering in a CSTR. Also Lakshmi Narayanan et al⁹ combined non-linear IMC, strong acid equivalent and an adaptive mechanism to control the pH in a CSTR.

However industry's need is for a cheap but effective solution to the problem to enable the legal requirements to be met the latest being the Environmental Act (1995) and to satisfy media pressure. Seider et al¹⁰ illustrated that advances in non-linear predictive control enable these criteria to be satisfied simultaneously. End of pipe solutions are much cheaper and more attractive to industry. Research in this area is incomplete and minimal. Examples of studies in this field; Rhinehart's¹¹ research concluded that dual in-line base injection is preferable to single in-line base injection for acidic effluent streams. Following this study Williams et al¹² applied Process Model-Based Control (PMBC) to a dual base injection system and yielded results that were more than comparable with CSTR solutions. More recently Shukla et al¹³ applied heuristic model control.

Gustafsson¹⁴ and Pröll et al¹⁵ studied control methods applied to plant design that combined the effective mixing of a CSTR with the in-line base injection approach. Karim et al¹⁶ used a process model based on the same system to test an adaptive radial basis function network.

Anti-logging Approach

The anti-logging approach is based upon research by Love^{17,18} and is a variable transformation approach. The pH measurement is anti-logged yielding a linear signal: the concentration of hydrogen ions, as depicted in Figure 1.

The conversion from pH to $[H^+]$ is calculated from:

$$\text{If } \text{pH} \leq 7 \text{ then } [H^+] = 10^{(6-\text{pH})} \text{ (mg/m}^3\text{)}$$

$$\text{If } \text{pH} \geq 7 \text{ then } [H^+] = -10^{(\text{pH}-8)} \text{ (mg/m}^3\text{)}$$

Alkaline solutions are considered to be negative acids. The hole in the scale at pH 7 is in significant; consequently, the concentration of hydrogen ions at this point is considered to be equal to zero. Note also that a

factor of 10^6 has been introduced to enable the $[H^+]$ concentration scale to be handled numerically within standard control algorithms and displays.

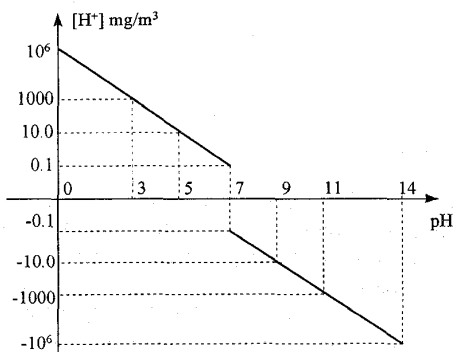


Figure 1: pH versus the hydrogen ion concentration

The hydrogen ion concentration in the stream leaving the mixing junction is the result of injecting the basic stream into the wild acidic stream, as illustrated in Figure 2.

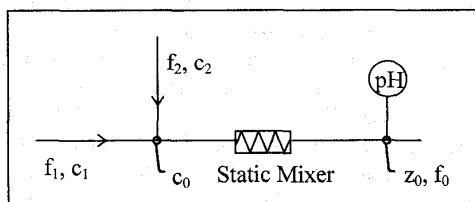


Figure 2: Mixing Junction

The unsteady state mass balance for concentration across the mixing junction;

$$f_0 \cdot c_0 = f_1 \cdot c_1 + f_2 \cdot c_2$$

If the desired pH of the mixed stream is neutrality then $c_0=0$, therefore

$$f_2 = -c_1 \cdot f_1 / c_2$$

The concentration of hydrogen ions at the point of the pH measurement downstream of the in-line mixer is the same as the concentration c_0 , except that it is delayed by time L due to distance velocity effects.

$$z_0 = c_0(t - L)$$

This is a variable transformation approach as infers pH control from hydrogen ion concentrations of the inlet streams.

Neutralisation Plant Design

The pH control pilot rig design is similar to the Gustafsson¹³ process, but replaces the CSTR with a back mixing tank, see Figure 3. Walsh¹⁹ concluded that the time delays associated with mixing effects in a CSTR and distance velocity effects in the external circulation loop of a back mixed tank are comparable, but it should be noted that both are small relative to the dominant first

order lag of the vessel itself. In terms of cost advantage, the back mixing tank design is better value than a CSTR as;

- a centrifugal pump is cheaper than a motor/agitator assembly for a given mixing duty.
- the pipe work associated with the pumped external circulation loop is cheaper than the supports, bearings and seals required for an agitator, especially if the vessel is under pressure or vacuum.
- there is invariably a need for a pump for product discharge anyway. This can be specified to meet the dual function of discharge and mixing.

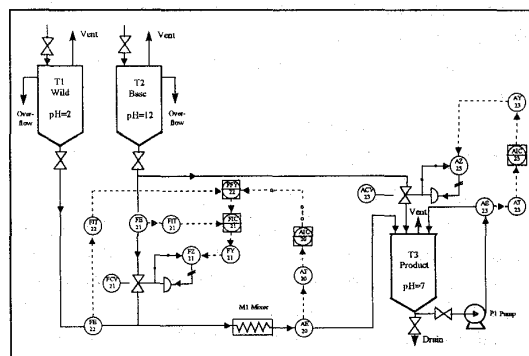


Figure 3: Pilot Neutralisation Plant P&I

Control Strategy

The wild acid stream (HCl) is neutralised by mixing it with two alkali streams (NaOH), the products of reaction being salt (NaCl) and water (H_2O).

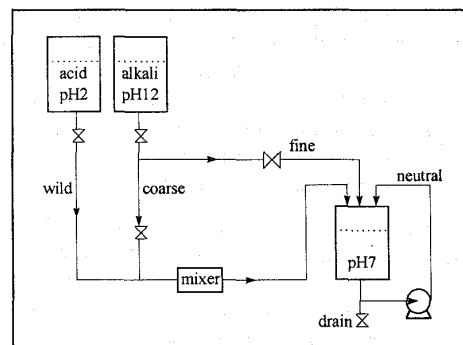
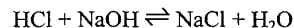


Figure 4: Two Control Stages of the Neutralisation Process

The neutralisation is carried out in two stages, as depicted in Figure 4. Firstly, a coarse adjustment is made using an 'in-line' mixer in which most of the neutralisation occurs. This in-line approach is typical of many effluent treatment plants. The second stage is a fine adjustment made using a mixing vessel and pump which completes the neutralisation. The use of the vessel is typical of many chemical process plants.

Whereas feedback control is retrospective, i.e. it corrects for errors that already exist, feedforward control predicts the control action required to prevent errors from occurring. Knowing the flow rate of acid f_1 and the strengths of the acid and alkali, the flow rate of alkali required for complete neutralisation may be calculated. The set point f_R of the coarse alkali flow control loop is set at about 95% of this value, as depicted in Figure 5.

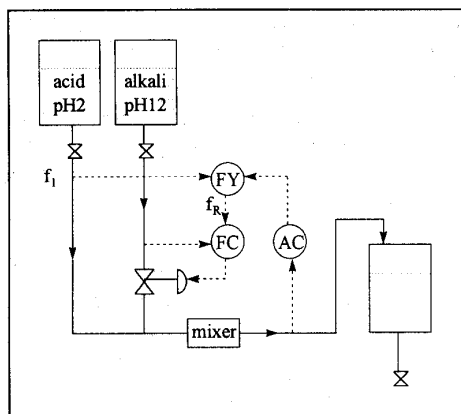


Figure 5: Coarse Control Loop

It is a well-known fact that feedforward controllers are susceptible to measurement errors, resulting in an off-set which may be substantial. So, a feedback controller using the downstream value z_0 is used to counter-act any offset. The feedback controller yields a scaling factor which trims the feedforward output f_R , to generate the remote set point for the cascade flow control loop on the coarse stream. The cascade flow control loop insulates the concentration control loop from disturbances due to pressure changes.

Good mixing is achieved in the receiver vessel by pumping the process liquor through an external circulation loop. The strength of the liquor is measured downstream of the pump and a conventional feedback controller is used to manipulate the fine alkali flow rate, as depicted in Figure 6. This flow corresponds to the remaining 5% or so of alkali required for neutralisation.

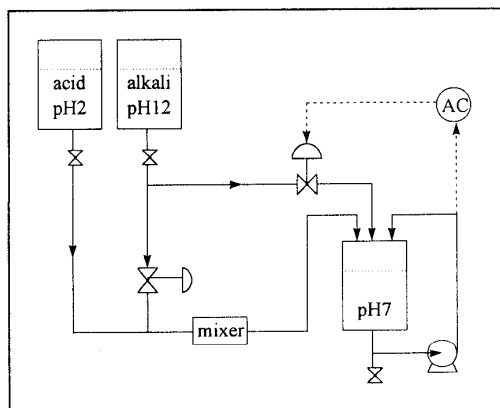


Figure 6: Fine Control Loop

Current Position

The effectiveness of the anti-logging approach combined with the control strategy has been demonstrated by means of simulation by Love¹⁷.

A pilot scale rig comprising the neutralisation process and industrial instrumentation for realising the control strategy has been developed. It is interfaced to both a Eurotherm SCADA and Honeywell DCS system and is currently being commissioned.

Empirical results of tests on the rig will be presented at the conference. Whereas the approach is known to be robust for strong acid/base neutralisations, it is not known how effective it is in the presence of buffering. It is hoped that the results on weak acid/base neutralisation will also be presented.

Future Work

There are two main components to the future work. Firstly, modifications may need to be made to accommodate buffering effects. One approach is to employ a model that describes the titration of a weak acid with a strong base as developed by Cardinali et al²⁰. An alternative to this is to use Atkins²¹ description of the titration curve. Another approach is to apply a modelling technique that characterises the flow of a plug of fluid along the mixing pipe and the rate of change of the chemical composition in the mixed stream, Bailey²²

Secondly is the anti-logging technique is to be used in conjunction with various alternative classical and modern control techniques. For example; Smith Predictor, Fuzzy Logic and Model Based Predictive Control (MBPC). Empirical and simulation results of applying such advanced control methods to the pH process will be presented at the conference.

Nomenclature

- c_1 $[H^+]$ for wild stream at the inlet to the mixing junction (mg/m^3)
- c_2 $[H^+]$ for base stream at the inlet to the mixing junction (mg/m^3)
- c_0 resultant $[H^+]$ at the outlet of the mixing junction (mg/m^3)
- z_0 $[H^+]$ for the mixed stream at the point of pH measurement (mg/m^3)
- f_1 the wild acid stream mass flow rate (Kg/s)
- f_2 the base stream mass flow rate (Kg/s)
- f_0 the resultant outlet stream mass flow rate (Kg/s)

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